INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS

2009 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

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ENVIRONMENT, SAFETY, AND HEALTH

SCOPE

The ESH section of the overall Roadmap is unusual in two respects. First, the principles of successful ESH program execution remain largely independent of the specific technology thrust advances to which they are applied. As a consequence, many ESH Roadmap elements, such as the Difficult Challenges, Technology Requirements, and Potential Solutions, can bear a strong similarity from one technology generation to the next. Therefore, the four basic ESH Roadmap strategies remain exactly as they were in the previous edition, namely:

- Understand (characterize) processes and materials during the development phase
- Use materials that are less hazardous or whose byproducts are less hazardous
- Design products and systems (equipment and facilities) that consume less raw material and resources
- Make the factory safe for employees

In applying these principles as integral elements to success, the industry continues to be an ESH as well as a technology leader. Semiconductor manufacturers have adopted a business approach to ESH which uses strategies that are integrated with manufacturing technologies, products, and services.

Second, while the Roadmap by intent and execution is a technology-focused document, the ESH section must necessarily comprehend and address various policy and regulatory issues. Failure to do so could place in jeopardy the implementation of successfully developed technologies. While such issues have always been indirectly addressed in the ESH Roadmap, here they are more explicitly recognized for the first time. This has led to the introduction of ESH Categories and Domains, as will be described in detail shortly.

The ESH roadmap identifies challenges when new wafer processing and assembly technologies move through research and development phases, and towards manufacturing insertion. Following the presentation of ESH Domains & Categories in Table ESH2, ESH technology requirements are listed in Tables ESH3–8. Potential technology and management solutions to meet these challenges are proposed in Figures ESH1–3. These challenges' successful resolution will best obtain when ESH concerns are integral in the thinking and actions of process, equipment, and facilities engineers; and also those of chemical/material and tool suppliers; and finally those of university and consortia researchers. ESH improvements must also contribute to – or at minimum, not conflict with – enhanced cost, technical performance, and product timing. They must inherently minimize risk, public and employee health effects, and environmental impact. Successful global ESH initiatives must be timely, yet far reaching, to assure long-term success over the Roadmap's life.

DIFFICULT CHALLENGES

The ESH Difficult Challenges (Tables ESH1a-1b) reflect inherent ESH science issues within the scope of evolving semiconductor technology (e.g., the need for nanomaterial assessment methodologies). In addition, in the past, the Difficult Challenges were the only opportunity to highlight any anticipated regulatory and legislative limitations to be incorporated into future technology planning. (As already stated, such limitations are given an expanded presence in this Roadmap.) Finally, the Difficult Challenges are the starting point for evaluating each technology thrust. This starting point for cross-thrust analysis provides information on needs to be incorporated into the ESH Technology Requirement tables.

The ESH Difficult Challenges are organized into four high level segments: Chemicals and Materials Management, Process and Equipment Management, Facilities Technology Requirements, and Sustainability and Product Stewardship. These segments also serve as the organizing scheme for the Technology Requirements tables.

Chemicals and Materials Management provides guidance (to academic and industry researchers; and process, equipment, and chemical/material developers) on identifying and addressing the ESH characteristics of potential new process chemicals and materials. This guidance is essential in selecting preferred chemicals and materials with minimal ESH impact. Determining the physical/chemical, environmental, and toxicological properties of chemicals and materials (as well as any reaction by-products) is essential to protecting human health and the environment, as well as minimizing business impacts after processes are developed and introduced into high volume manufacturing. *Refer to the chemical screening tool (Chemical Restrictions Table) online.*

Process and Equipment Management focuses on process and tool design, emphasizing the need for processes and equipment development that meet technology demands, while also reducing impacts on human health, safety, and the environment. Equipment design should minimize the potential for chemical exposures, the need for personal protective equipment (PPE), and ergonomic issues. Another important goal is resource conservation (water, energy, and chemicals/materials) through process optimization and implementing cost-effective use reduction solutions such as reduced utility consumption during tool idle periods. \Goals should be applied to process equipment and support equipment such as pumps, chillers and point of use abatement. Replacing hazardous chemicals/materials with more benign ones, managing process emissions and byproducts, and reducing consumables are also important considerations in tool design and operation. Design for ease of maintenance and equipment end-of-life are additional challenges.

Facilities Technology Requirements focuses on fab support systems, emphasizing the need for ESH-friendly design and operation of factories and support systems. Resource conservation (water, energy, chemicals/materials, and consumables) through more efficient cleanroom design, air management, heat removal, and demand-based utility consumption is required. Facility design must be flexible while maintaining efficiency through real-time control. Another consideration is designing factories for end-of-life re-use, especially as factory sizes and building costs increase.

Sustainability and Product Stewardship have become increasingly important business considerations. To address these challenges in a cost-effective and timely way, sustainability metrics are required. In addition, Design for Environment, Safety, and Health (DFESH) should become an integral part of the facility, equipment, and product design as well as management's decision-making. Environmentally friendly end-of-life reuse/recycle/reclaim of facilities, manufacturing equipment, and industry products are increasingly important to serve both business and ESH needs.

Table ESH1a ESH Difficult Challenges—Near-term

Difficult Challenges ≥ 16 nm	*Summary of Issues*
Chemicals and materials management	• *Chemical Assessment*: There is a need for robust and rapid assessment methodologies to ensure that new chemicals/materials can be utilized (without delay) in manufacturing, while protecting human health, safety, and the environment. Given the global movement possible for R&D, pre-manufacturing, and full commercialization, these methodologies must recognize regional regulatory/policy differences, and the overall trends towards lower exposure limits and increased monitoring. • *Chemical Data Availability*: There is incomplete comprehensive ESH data for many new, proprietary chemicals/materials, to be able to respond to the increasing regulatory/policy requirements on their use In addition; methods for anticipating and forecasting such future requirements are not well developed. • *Chemical Exposure Management*: There is incomplete information on how chemicals/materials are used and the process by-products formed. Also, while methods used to obtain such information are becoming more standardized, their availability varies depending on the specific issue being addressed, and can use improvement.
Process and equipment management	• *Process Chemical Optimization* There is a need to develop processes and equipment meeting technology requirements, while also reducing their impact on human health, safety and the environment (e.g., using more benign materials, reducing chemical quantity requirements by more efficient and cost-effective process management). • *Environment Management:* There is a need to understand ESH characteristics, and to develop effective management systems, for process emissions and by-products. In this way, the appropriate mitigations (including the capability for component isolation in waste streams) for such hazardous and non-hazardous emissions and by-products can be addressed. • *Global Warming Emissions Reduction*: There is a need to reduce emissions of high GWP chemicals from processes which use them, and/or produce them as by-products. • *Water and Energy Conservation:* There is a need for innovative energy- and water-efficient processes and equipment. • *Consumables Optimization:* There is a need for more efficient chemical/material utilization, with improved reuse/recycling/reclaiming of them and their process emissions and byproducts. • *Byproducts Management*: There is a need for improved metrology for byproduct speciation. • *Chemical Exposure Management:* There is a need to design-out chemical exposure potentials and the requirements for personal protective equipment (PPE) • *Design for Maintenance:* There is a need to design equipment so that commonly serviced components and consumable items are easily and safely accessed, with such maintenance and servicing safely performed by a single person with minimal health and safety risks. • *Equipment End-of-Life:* There is a need to develop effective management systems to address issues related to equipment reuse/recycle/reclaim.
Facilities technology requirements	• *Conservation*: There is a need to reduce energy, water and other utilities use, and for more efficient cleanrooms' and facilities systems' thermal management. • *Global Warming Emissions Reduction*: There is a need to design energy efficient manufacturing facilities, to enable reducing total CO_2 equivalent emissions.
Sustainability and product stewardship	• *Sustainability Metrics:* There is a need for methodologies to define and measure a technology generation's sustainability. • *Design for ESH:* There is a need to make ESH a design-stage parameter for new facilities, equipment, processes and products. • *End-of-Life Reuse/Recycle/Reclaim:* There is a need to design facilities, equipment and products to facilitate these end-of-life issues

Table ESH1b ESH Difficult Challenges—Long-term

Difficult Challenges < 16 nm	*Summary of Issues*
Chemicals and materials management	• *Chemical Assessment*: There is a need for robust and rapid assessment methodologies to ensure that new chemicals/materials can be utilized (without delay) in manufacturing, while protecting human health, safety, and the environment. • *Chemical Data Availability*: There is incomplete comprehensive ESH data for many new, proprietary chemicals/materials, to be able to respond to the increasing regulatory/policy requirements on their use • *Chemical Exposure Management*: There is incomplete information on how chemicals/materials are used and the process by-products formed.
Process and equipment management	• *Chemical Reduction*: There is a need to develop processes and equipment meeting technology requirements, while also reducing their impact on human health, safety and the environment (e.g., using more benign materials, reducing chemical quantity requirements by more efficient and cost-effective process management). There is a need to reduce emissions of high GWP chemicals from processes which use them, and/or produce them as by-products. • *Environment Management:* There is a need to understand ESH characteristics, and to develop effective management systems, for process emissions and by-products. In this way, the appropriate mitigations for such hazardous and non-hazardous emissions and by-products can be addressed. • *Water and Energy Conservation:* There is a need to reduce water and energy consumption, and for innovative energy- and water-efficient processes and equipment. • *Consumables Optimization:* There is a need for more efficient chemical/material utilization, with their increased reuse/recycle/reclaim (and of their process emissions and byproducts). • *Chemical Exposure Management:* There is a need to design-out chemical exposure potentials and personal protective equipment (PPE) requirements. • *Design for Maintenance:* There is a need to design equipment so that commonly serviced components and consumable items are easily and safely accessed, with such maintenance and servicing safely performed by a single person with minimal health and safety risks. • *Equipment End-of-Life:* There is a need to develop effective management systems to address issues related to equipment reuse/recycle/reclaim.
Facilities technology requirements	• *Conservation*: There is a need to reduce energy, water and other utilities use, and for more efficient cleanrooms' and facilities systems' thermal management. • *Global Warming Emissions Reduction*: There is a need to design energy efficient manufacturing facilities, to enable reducing total CO_2 equivalent emissions.
Sustainability and product stewardship	• *Sustainability Metrics:* There is a need for methodologies to define and measure a technology generation's sustainability, and also sustainability at a factory infrastructure level. • *Design for ESH:* There is a need to make ESH a design-stage parameter for new facilities, equipment, processes and products, with methodologies to holistically evaluate and quantify the ESH impacts of facilities operations, processes, chemicals/materials, consumables, and process equipment for the total manufacturing flow. • *End-of-Life Reuse/Recycle/Reclaim*: There is a need to design facilities, equipment and products to facilitate these end-of-life issues

TECHNOLOGY REQUIREMENTS

ESH CATEGORIES AND DOMAINS

Previous ESH Roadmap versions have presented a requirements set which relates to both the technical thrusts having ESH concerns (Interconnect, Front End Processes, Lithography, Assembly & Packaging, Emerging Research Materials), as well as to ESH concerns which are broader and more general than those pertaining to a single technology thrust (Intrinsic). Those requirements have typically been presented as undifferentiated: other than occasional comments highlighting areas of potentially higher concern, it was not possible for the Roadmap's audience to readily prioritize the requirements shown.

Whatever this approach's past merits, it no longer best serves the industry's needs. Some ESH requirements relate to actual or possible regulatory/policy concerns; some come with the potential for significant additional process benefits when implemented; and finally, some provide important ESH benefits, but without the added secondary benefits possible in the first two areas. Thus, given the limited resources available to address the total requirements set above, it is appropriate to provide guidance towards those areas of greatest added benefit, in addition to the ESH improvements gained. To this end, all ESH requirements have now been placed in one of three Categories:

- Critical: Any requirement in this category is an essential item for technology success/implementation as well as ESH benefits. If not addressed, it could compromise the technology's ability to insert into manufacturing, based on potential or existing policy/regulatory issues (whether internally or externally driven) in at least one of the ITRS member regions. These requirements have the highest priority for action.
- Important: Any requirement in this category is a key item for process success as well as ESH benefits. If not addressed, it could compromise the technology's cost of ownership (CoO) in manufacturing, based on factors such as throughput, yield, and chemical/material and/or tool costs (including disposal/abatement). These requirements have the next highest priority for action.
- Useful: Any requirement in this category is a key item for ESH benefits ("best practices"), but without any clear additional factors which would place it in either of the above two categories. If not addressed, it could compromise the technology's ability to achieve the lowest ESH impact when inserted into manufacturing. These requirements have a lower priority for action.

Requirements in the Critical category are generally not difficult to define, based on an understanding of policy/regulatory actions underway or being contemplated. Some judgment is needed in distinguishing between Important and Useful: how large should a CoO benefit be to categorize an item as Important? The decisions made here are thus by nature inexact, but provide a starting point for further consideration and updates in future Roadmaps.

The Requirements tables will contain only the Critical and Important items, as those on which attention and resources are best focused. All requirements in all Categories are presented in an ESH Domains table (Table ESH2). The Domains chosen are not unique, but simply selected to provide a set of unifying ESH elements for the single presentation of the full set of items in all three Categories:

- Restricted Chemicals. By nature, this Domain highlights chemicals which fall into the Critical Category
- New Chemicals. There are a variety of emerging chemicals and materials, the exact specifications and ESH properties of which are not always fully established when they enter into new process consideration.
- Nanotechnology. While formally only a subset of New Chemicals, there can be unique ESH issues with nanometer-scale chemicals and materials, which merit their separation into their own Domain.
- Utilization/Waste Reduction. The four basic ESH strategies defined in the Scope all have a prominent role in this Domain.
- Energy. Given the increasing attention to greenhouse gas control, carbon footprint, and similar energy-control metrics, this area stands out as one deserving attention at the Domain level.
- Green Fab. This is a broad – and at present not-well-defined or universally agreed-on – term meant to represent fab operations conducted with minimal ESH impact (and the process and economic benefits which may derive

from such practices). This Domain includes sustainability issues, as well as the full life-cycle considerations for chemicals/materials, tools and processes, the full fab infrastructure, and the products derived from them.

Finally, for all the succeeding Intrinsic and Technology Requirements tables, the Category designations are applied only to the *ESH#a* tables representing the near-term years, and not to the *ESH#b* tables representing the long-term years, for two reasons. First, the likely long-term value can be inferred from the near-term table entry. Second, there is generally not a precise assessment of this Category in the long-term years; however, with the extended timing, there is opportunity to revise the designation in later Roadmap versions.

ESH INTRINSIC REQUIREMENTS

Scientists and engineers responsible for new technology development require an explicit target set for ESH-related technology decisions, to complement the mainstream technology objectives. For example, in the past, a little-changing chemicals/materials set could readily support multiple technology generations. However, today each emerging technology generation typically requires one or more new chemicals/materials whose ESH assessment is a critical element to their introduction. Process chemistries, including characterizing emissions and byproducts, must be understood so that their use with minimal ESH impact can be defined. In addition, risk assessments should include a check of *Chemical Restrictions Table*, to determine if any chemicals/materials are banned or under regulatory watch. ESH impact assessments should include material balances, and should identify paths by which chemicals/materials may enter the environment. Table ESH3 outlines these ESH goals for those items in the Critical and Important Categories (with the Useful items shown under the Intrinsic sub-headings in Table ESH2).

TECHNICAL THRUST ESH TECHNOLOGY REQUIREMENTS

The specific ESH technology requirements for each technical thrust (i.e., Interconnect, Front End Processes, Lithography, Assembly and Packaging, and Emerging Research Materials) can be found in Tables ESH4 and ESH5, which correspond to two of the four ESH Difficult Challenges themes (Chemicals and Materials Management, and Process and Equipment Management). ESH requirements were established based on mapping the technical thrust needs against the ESH Difficult Challenges. In many cases, the goals are to establish baselines for process chemical utilization and process emissions, to improve these baseline values over time, and to identify ESH-friendly alternative chemicals or processes. Values of 10% improvement are often proposed. These are clearly not precise targets, as specifying such exact goals for many different process types is beyond the ESH Roadmap's scope. Rather, such goals serve as placeholders for the strategy of continuous improvement from these baselines over time, making step changes as feasible when new technology generations appear. Worker protection measures should address chemical hazards as well as potential physical hazards (such as thermal, non-ionizing radiation, laser, and robotics hazards), with equipment maintenance operations a particular concern.

As process equipment size and complexity increase with advancing technologies, tool design for safe and ergonomically friendly maintenance becomes more challenging. Meeting such challenges is in keeping with the industry's established history of safe factories and low work-related injuries. Increases in wafer size and process throughput will require wafer-handling systems (including automated wafer transport systems and their interfaces with process equipment) that may increase worker risk during operation and maintenance. Therefore, design-stage controls and procedures (emphasizing ergonomics and robotics) to improve equipment operability and to prevent incorrect operation must be integral to such process development.

The specific thrust-based technology requirements and potential solutions are discussed below.

INTERCONNECT

Through the middle of the next decade, leading-edge interconnect technology can be expected to generally follow that which has served the industry for the past ten years: copper-based metallization and low-k dielectrics, following dual damascene processing approaches. However, within that general evolution, there will be a number of chemical/material changes, as well as process modifications, whose ESH implications must be considered. For metallization, these may include new formulations for copper ECD (including extending copper plating bath life or recycling), changes in barrier and nucleation films (especially if the dominant PVD processes move towards CVD/ALD processes), and the emergence of new capping layers and processes. For the dielectrics, increasingly porous films can involve new precursors and so new process emissions, all of which must be evaluated for ESH concerns. Such dielectrics can also require pore sealing agents. Finally, the supporting technologies of planarization and surface treatment will also evolve as any of the interconnect stack's films change, and the same ESH considerations must apply there as well.

Planarization's increasing use presents particular issues both in consumables (e.g., slurries, pads, and brushes), as well as major chemicals and water use. Therefore, efforts should be made to develop planarization processes that will reduce overall water consumption. Water recycle and reclaim for planarization and post-planarization cleans is a potential solution for water use reduction.

High GWP (global warming potential) PFCs (perfluorocompounds) are used extensively in interconnect dry etch and chamber cleaning applications. For chamber cleaning, processes that do not use PFCs have been evaluated; note, however, that the residues of carbon-containing low-k films which are processed in such chambers can produce PFC emissions (e.g., CF_4) in any case. At present, dry etch processes for low-k dielectrics are all based on fluorocarbon compounds (whether or not they fall into the high GWP PFC family), and so PFC emissions as either byproducts or unreacted starting compounds must be managed. The semiconductor industry's near-term goal is to reduce absolute PFC emissions 10% from the 1995 baseline by 2010. To achieve this aggressive goal, and to ensure that these chemicals remain available for industry use, the industry must strive to reduce PFC emissions by process optimization, alternative chemistries, and/or abatement. Fluorinated heat transfer fluids also have high global warming potential, and these materials' emissions must be minimized. Another high GWP process chemical to be addressed is N_2O (used in oxynitride deposition processes).

With the emergence and expected rapid growth of chip-to-chip interconnects (commonly referred to as 3D technology), a new source of substantial PFC use has appeared, with processes based on PFCs such as sulfur hexafluoride being developed for through-silicon via etch. This new application will place even greater demands on maintaining the PFC reduction goals versus the 1995 baseline.

To meet expected energy conservation goals, equipment (plasma-enhanced CVD, dry etch, and CMP) power requirements must be minimized. These goals should include reducing support equipment energy consumption. Plasma processes are both energy-intensive and inefficient in the way they use input chemistries (e.g., often achieving only 10–30% dissociation, by design, in etch processes). Future generation tools will require R&D in low energy-consuming plasma systems. Etchers and CVD tools use point-of-use (POU) chillers and heat exchangers to maintain wafer and chamber temperatures in a vacuum. More efficient heating and cooling control systems (including eliminating simultaneous heating and cooling for temperature control devices) could help decrease energy use and improve control. Greater use of cooling water to remove heat from equipment, rather than dissipating heat into the cleanroom, results in fab energy savings.

By the middle of the next decade, entirely new interconnect materials set may begin to emerge, including non-metallic conductors (likely based on carbon nanomaterials technology) and air-gap dielectrics (using fugitive materials). Thus, entirely new sets of chemical/materials and process emissions will need to be examined for ESH concerns – especially given the incomplete current definition of nanomaterials' ESH properties. Finally, with such a dramatic shift in the interconnect films, there is potential for additive processing of such materials. This is a radical shift from decades of lithography-based subtractive processing, but the ESH benefits which would obtain, along with the process simplification advantages, should be substantial.

Potential solutions for interconnect include additive processing, low ESH impact CMP processes (e.g., slurry recycle or slurry-less CMP), non-PFC emitting through-silicon via etch, low cost/high efficiency plasma etch emissions abatement, low temperature wafer cleaning, reduced volume process chambers for CVD and ALD, improved ALD process throughput (to reduce resource requirements), vacuum pumping with process-tool-demand-based speed control, reduced dependencies on high temperatures (both internal and external to the processes), and implementing variable modulation for heating and cooling devices.

FRONT END PROCESSING

Front end chemicals/materials challenges include the evolution of precursors and processes included in this thrust: substrates, dopants, gate stacks, conductors and insulators for contact applications, memory structures, and the variety of supporting chemicals and processes. All these applications should comprehend the ESH concerns of chemical/material selection for reduced ESH impact, and efficient use of natural resources such as water and energy in tools and processes. These principles should be applied throughout this thrust, as exemplified in the examples below.

ESH concerns for surface preparation focus on new clean techniques, chemical/material usage, and water and energy consumption. Chemical use optimization should be applied to both conventional and alternative cleaning processes. Fluid flow optimization and sensor-based process control can provide both ESH and process advantages.

Alternative clean processes (e.g., dilute chemistries, solvent-based, sonic energy enhancement, simplified process flows, DI/ozone, gas phase, cryogenic, hot-UPW) should be pursued to reduce ESH hazards and chemical consumption. The impact of alternative cleaning methods on energy consumption should be considered. Sustainable, optimized water use strategies such as more efficient UPW production, reduced water consumption, and efficient rinsing all contribute to enhanced ESH performance.

As wet-tool designs enable such enhancements, attention should be paid to controlling process emissions, ergonomic and robotics safety principles, and ease and safety of equipment maintenance. The trend towards single-wafer cleaning needs to be managed for efficient use of chemicals and resources.

While CMP processes in the front end are generally fewer than for interconnects, they still apply in areas such as shallow trench isolation (STI) and contact metallization. The ESH issues common to all CMP processes – chemicals, consumables, and water optimization (including recycle/reclaim in the last case) – are important here.

New gate stack materials (both high-κ and electrode) require assessing potential hazards associated with both the precursors, as well as their associated deposition and etch processes. Thus, precursor ESH properties, and of process byproducts, must be understood so that engineering controls and any needed personal protective equipment can be utilized. These processes should be optimized for maximum chemical utilization and efficient energy use.

As doping technologies evolve, there will be a continuing need to properly manage reactive hydrides (SiH_4, B_2H_6, PH_3, SbH_3, AsH_3, possibly others) and metal alkyls. Sub-atmospheric delivery systems have proved effective for their ESH benefits, and their use should expand in this area.

As for Interconnect, PFC use in front end plasma etch and chamber clean processes will be challenged by both general ESH considerations, as well as the industry's near-term goal to reduce absolute PFC emissions 10% from the 1995 baseline by 2010. Here again, the industry must strive to reduce PFC emissions by process optimization, alternative chemistries, and/or abatement. As another high GWP process chemical, N_2O's emissions from furnace nitride processes should be characterized and minimized.

Emerging technologies for new channel materials involve both heavy metals and arsenic, all of which are coming under increasing regulatory scrutiny, along with the overall ESH concerns for understanding and proper management of the precursors, and the processes using them. In addition, new channel materials may necessitate a move away from traditional cleaning chemistries and processes. ESH considerations must be accounted for during the identification and selection of these new cleaning processes. Similarly, new memory technologies are proposing new heavy metals usage, and the same scrutiny must be applied here.

Potential solutions for FEP include alternative surface preparation methods with dilute chemistries and increased chemical utilization, additive processing, non-PFC emitting etch processes, low temperature wafer cleaning, high efficiency rinses, and new energy efficient thermal processes.

LITHOGRAPHY

Lithography's ESH issues can be divided into three topical areas: 1) photomask manufacturing chemical/materials and processes 2) hardware and processes in the litho cell (the [typically] integrated combination of wafer track and exposure system), and 3) the chemicals/materials and consumables used in the litho cell. Each of these areas will be reviewed in turn.

The photomask manufacturing process shares some common features with the other two areas, notably ESH assessment and optimization of the chemicals used and emissions generated. These concerns will include assessments of chemical toxicity, health risks, and particular emission issues pertaining to hazardous air pollutants (HAPs), volatile organic compounds (VOCs), PFOS/PFAS/PFOA use, and persistent, bioaccumulative, toxic (PBT) compounds. For conventional chrome-on-glass photomasks, there are still evolving requirements which will need to be understood and managed for deposition, etching, and cleaning process steps. Importantly, as EUV technology emerges as the replacement for 193nm in flood exposure lithography, a new set of chemicals/materials, consumables and processes – potentially all quite different from the current 193nm technology – will need to be assessed in detail.

Litho cell ESH concerns for the evolving incumbent 193nm technology include ergonomic equipment design, understanding and minimizing potential worker exposure to toxic materials and hazardous energies; controlling emissions of HAPs, VOCs, and PBTs; minimizing hazardous waste generation; and reducing resource consumption. For example, it is desirable to reduce process vulnerabilities to fab and equipment air through isolation, since the current stringent environmental control for process and equipment stability increases energy consumption for both equipment and facilities. These concerns also apply to the emerging EUV technology, but in addition, energy consumption is becoming a major area to be addressed. The following analysis is only semi-quantitative, but serves to illustrate the magnitude of the concern. According to the Yield Enhancement thrust, a leading edge fab today consumes about 18 MW of power.

According to the Lithography thrust, a single EUV exposure tool is expected to draw 0.5-2 MW. For a fab containing 10 such tools, at the lower end of this range, any energy reduction goals from current baselines would be extremely demanding on other process areas; at the upper end of the range, they become completely infeasible. As energy metrics, carbon footprint, and greenhouse gas emission goals become a larger part of the industry's thinking, this is a major issue which will have to be addressed.

For the litho cell chemicals/materials and consumables, the above comments on photomask manufacture serve as a starting point. An ongoing critical need is the identification of alternatives to the PFOS contained in developers, etchants, anti-reflective coatings (ARCs), and photoacid generators (PAGs) in chemically amplified resists. Ultimately, compositions free of any PFOS/PFAS/PFOA species should be developed. Water immersion lithography also results in process changes where new compositions such as water resistant photoresists and anti-reflective coatings must be assessed. In addition, with the advent of 193nm double processing schemes, new types of chemicals are appearing, such as those for "resist freeze" processes. Finally, as for the litho cell processes, a wavelength shift from 193nm to EUV at 13.5nm will bring its own set of changes in photoresists and all the ancillary chemicals which surround them, and whose ESH impacts must be assessed and optimized.

Finally, while the above discussion has focused on the 193nm and EUV exposure technologies, there are patterning alternatives under study, notably imprint and e-beam direct writing. All of the concerns for the current exposure technologies in tooling, processes, and chemicals/materials, will apply in their own way to these areas as well.

Among the potential solutions for lithography are rapid ESH assessment of new lithography materials, use of sustainable chemistries, development of chemistries free from PFOS/PFAS/PFOA, improved chemical utilization, and application of pollution prevention and DFESH principles when designing new equipment and processes. As noted above, EUV exposure tools have significant energy requirements, and energy efficient 13.5 nm sources should be sought. All equipment design of should also include effective radiation shielding, minimized ergonomic stressors, and adherence to SEMI S2, S8, and S23 guidelines.[1] Long-term potential solutions include designing novel patterning equipment for efficient materials use.

ASSEMBLY AND PACKAGING

The trend away from conventional leaded single-chip packages − and towards for example, multi-chip forms (e.g. system in package), as well as chip-scale and flip-chip packaging − can improve ESH metrics by reducing or eliminating leadframes and conventional molding. While potentially reducing the total ESH impact, multi-chip packaging introduces new chemistries and processes (e.g., wafer thinning) with associated ESH concerns. The use of environmentally hazardous assembly and packaging materials, such as lead, hexavalent chromium, beryllium, antimony, and brominated flame retardants is under increasing international regulatory pressure and restrictions. As with many other process types, the tooling used should have reduced ESH impact as attention is paid to energy and water use, and to ergonomic, use, and maintenance issues at both the design and operation phases.

A significant issue for 3D technology has already been noted for Interconnect, but it is one shared with Assembly & Packaging: silicon through-via etch processes based on PFCs such as sulfur hexafluoride will place even greater demands on reaching and holding the industry's PFC reduction goals.

Potential solutions for assembly and packaging include developing key environmental performance indicators; eliminating potentially restricted chemicals; adopting no/low-curing plastics; recyclable packaging materials; and etch processes which eliminate PFC emissions (either by improved dry etch processes and/or emissions control, or a process switch to precision laser drilling for 3D interconnects).

EMERGING RESEARCH MATERIALS

Among the proposed new materials are those which contain metals which are currently little-used in semiconductor manufacturing. Understanding their ESH properties, and the potential policy/regulatory restrictions on their use, will be critical to formulating plans for their further development and manufacturing applications.

Also, as nanometer-scale semiconductor manufacturing chemicals/materials come into wider use (beyond those currently found in, say, CMP slurry particles), there should be increased focus on these materials' ESH properties. It is well known

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[1] *SEMI. S2—**Environment, Health and** Safety Guidelines for Semiconductor Manufacturing Equipment*
SEMI S8—Safety Guidelines for Ergonomics Engineering of Semiconductor Equipment
SEMI S23 - Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment

that nano-sized materials can have unique and diverse properties compared to their macro/bulk (even at micron dimensions) forms. These differences must be understood for the unique ESH challenges they may present. In addition, the new materials' small size may make standard ESH controls (e.g., emission control equipment) less than optimal. As a result, the following ESH considerations should be taken into account for future technology development:

- Developing effective monitoring tools to detect nanomaterials' presence in the workplace, in waste streams, and in the environment.
- Evaluating and developing appropriate protocols to ensure worker health and safety.
- Evaluating and developing emission control equipment to ensure effective treatment of nanomaterial-containing waste streams.
- Understanding new nanomaterials' toxicity as it may differ from their bulk forms. This goal involves both developing rapid nanomaterials toxicity assessment methods, as well as nanomaterials toxicity models.

Potential solutions for emerging research materials include the development and implementation of ESH risk assessment methodologies for nanomaterials. Refer to the *Emerging Research Materials* chapter.

FACILITIES

Factory planning, design, and construction considerations are integral to responsible ESH performance for the semiconductor industry. Table ESH6 establishes such goals for factory design and operation. Factory design and the interfaces between factory, equipment, and workers strongly influence the industry's ESH performance. Standardization of safety and environmental systems, procedures, and methodologies (when applicable) will prove to be an efficient and cost-effective approach. Sharing these practices can reduce start-up schedules and will result in greater equipment supplier cooperation for interfacing their products into factories. Early comprehension of safe and environmentally responsible design, coupled with an understanding of code and regulatory requirements, is essential for designers to develop factories that meet ESH expectations, reduce start-up schedules, and avoid costly retrofits and changes. This is especially important as the industry considers the transition from 300 to 450 mm wafers, which require larger process tools and potentially greater quantities of chemicals and resources.

Accepted protocols for risk management, in order of priority, are hazard elimination, engineering controls, administrative controls (procedural), and personal protective equipment.

One opportunity for greater standardization is with manufacturing and assembly/test equipment. Standardization of equipment design, design verification, ESH qualification, and signoff will improve ESH performance, start-up efficiency, and cost. Additionally, ESH practice standardization in equipment maintenance, modification, decommissioning, and final disposition will also reap substantial ESH performance and cost improvements over the life of equipment and factories.

Standardization of building safety systems, and their process equipment interfaces, will improve safety and also increase installation efficiency and reduce start-up time. This standardization would include, but is not limited to, fire detection and suppression systems (and their monitoring interfaces), gas detection systems, electrical and chemical isolation devices, emergency shut-off systems, and safety-related alarms.

Additionally, the careful selection of process and maintenance chemicals addressed in other Roadmap sections should be complemented by designs that serve to isolate personnel from equipment during operation and maintenance.

The safety issues associated with factory support systems must also be aggressively improved in future factories. Improved risk assessment methodologies and their consistent utilization during the design phase will enhance this effort.

A thorough understanding of potential safety risks associated with automated equipment will drive the standards development to assure safe working conditions. These standards and guidelines must be integrated into the automated systems, the process equipment with which they interface, and the interfaces themselves. Additionally, factory planning and layout should include ergonomic design criteria for wafer handling, especially for 450 mm wafers.

The industry faces increasing permit, code, and emissions limitations. Future factory planning (and for existing factory modifications) should involve cooperative efforts (on a global level) with code and government bodies, to ensure that equipment and factory technology advances are comprehended and used in new and updated regulations. The semiconductor industry should move to establish basic ESH specifications that apply to all equipment and factory practices worldwide.

Factory design defines the systems that deliver process materials to process equipment, that manage byproducts, and that control the workplace. Future factory design must balance resource conservation, reduction, and management. These conservation and reduction programs are driven by increasing competition for limited water and energy resources, pollution concerns, and industry consumption of these limited resources.

ESH standardization and design improvements for factories and equipment can be greatly enhanced through training programs established for and by the industry. Technology now allows for computer-based training (CBT) programs to be developed to address all of this section's design and procedural challenges.

Increases in wafer size and process steps, as well as the need for higher purity water and chemicals/materials, indicates a trend for greater resource (water, energy, and chemicals/materials) usage per wafer. This trend can be reversed by developing higher efficiency processes and tools, and by adopting strategies such as recycling of spent chemicals, water, and waste for process applications and reuse for non-process applications. Resource utilization efficiency in semiconductor tools can be improved.

Most water used in semiconductor manufacturing is ultrapure water (UPW). Since the UPW production requires large chemical quantities, a UPW consumption and quality increase results in greater chemical consumption (and UPW production cost). A UPW consumption decrease will reduce both chemicals' environmental effects, as well as manufacturing costs. Recycling higher quality water for process applications, and reusing lower quality water for non-process applications, are both important. Where water is plentiful, wastewater recycling will depend on local water reuse options and associated recycling costs.

Energy source limitations could potentially restrict the industry's ability to expand existing factories or build new ones. Continual evolution in processes, products and product volume requires design for flexibility and modulation without compromising energy efficiency. While semiconductor manufacturers have demonstrated improved energy efficiencies over the past decade, potential resource limitations require the industry to continue the trend. Significant efficiency improvement opportunities include vacuum pumps, POU chillers and heaters, uninterrupted power systems, and power transforming devices (for example, RF generators and transformers). Besides the need for more energy efficient tools (with the potential emergence of EUV lithographic tools being a major concern), it is necessary to reduce tools' heat load/impact of the on the cleanroom, and to enhance idle mode tool capabilities.

While much of the responsibility for resource reduction and waste minimization rests with equipment suppliers and process technologists, applying advanced resource management programs to factory systems will have a significant impact as well. These future programs' goal is to build factories that minimize resource consumption and maximize the reuse, recycle, or reclaim of byproducts, moving towards near-zero-discharge factories. Key factory-related ESH programs require water reuse in process and non-process applications, energy efficient facilities equipment, improved facilities system design, and new facilities operating strategies.

Potential solutions for factory integration include developing and implementing semiconductor facility-specific LEED[2] practices; integrating idle mode capabilities into facilities systems; modulation approaches which are both local (e.g., variable speed control, solid state heating/cooling) and factory wide (e.g., modular control); and developing real-time on-line sensors (including speciation) for UPW recycling.

SUSTAINABILITY AND PRODUCT STEWARDSHIP

Table ESH7, although short, spans all areas of semiconductor product design and process development. It outlines criteria for sustainability and environmentally sound design of products, processes, equipment, and facilities.

Climate change is a universally recognized 21st century global environmental challenge, driving international efforts to reduce not only emissions of semiconductor manufacturing greenhouse gases (e.g., PFCs, N_2O, fluorinated heat transfer fluids), but also carbon dioxide emissions. Carbon footprint (a means to track a product's or process' impact on global climate) is defined as the total greenhouse gas amount emissions over a product's full life cycle, including the CO_2 from electricity generation. A reduced carbon footprint is vital to the industry's sustainability; therefore, carbon footprint metrics should be developed to track progress. Desirably, semiconductor devices are essential to improving the carbon footprint of both the products and the systems in which they are used.

Design for ESH (DFESH) is the term applied to ESH improvements' integration and proliferation into technology design. It allows for the early evaluation of ESH issues related to critical technology developments, and it ensures that there are no ESH-related "show stoppers." DFESH requires a comprehensive understanding of tools and materials development, facility design, waste and resource management, and their effects on ESH performance. DFESH incorporates ESH

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[2] *LEED – Leadership in Energy and Environmental Efficient Design*

improvements into the way products are manufactured, while maintaining desirable product price/performance and quality characteristics.

Finally, attention should be given to the design of facilities, equipment, and products for ease of disassembly and re-use at end of life.

Potential solutions for sustainability and product stewardship include the development of KEPIs to measure improvements in environmental impact of products, materials, processes, and facilities over subsequent technology generations.

FUTURE CONSIDERATIONS FOR 450MM

The current Roadmap guidance indicates 450 mm wafer processing in 32nm pilot lines in 2012, moving to full production at 22nm in 2014. For chemicals, the goal is to remain constant, and aim to reduce consumption, on a normalized (per cm^2) basis. There are currently goals being developed by industry groups to hold energy, water, and air emissions constant on an absolute (per wafer) basis. Such very aggressive goals (given the more than doubling of the wafer surface area to be processed versus 300mm) will need to be updated and reassessed in future Roadmap editions.

Table ESH2 ESH Requirements by Domain and Category

Restricted Chemicals Assembly & Packaging 3D via etch **C** FEP Plasma Etch **C** Doping **C** Interconnect Plasma etch **C** CVD chamber clean **C** 3D via etch **C** Lithography PFOS/PFAS/PFOA materials **C**	**New chemicals** Intrinsic Chemical risk assessments **U** ERM Materials for novel logic & memory **C** FEP High-k & gate materials **I** Alternative surface prep **U** Non-silicon, active substrates [channel] **C** Novel memory materials **I** Interconnect Low-k materials **I** Copper dep processes **I** Advanced conductors **U** Planarization **I** Surface prep **I** Lithography 193 immersion resists **U** EUV resists **U** Imprint materials **U**	**Nanotechnology** Intrinsic Nanomaterials risk assessment methods **U** ERM Nanomaterials **C**
Utilization/Waste Reduction Intrinsic Surface preparation UPW use **I** Tool UPW usage **I** Assembly & Packaging Die thinning **U** Molding processes **U** Waste & by-products **U** 3D via etch **C** ERM Nanomaterials **C** Materials for novel logic & memory **C** Factory Integration Non-hazardous solid waste **U** Hazardous waste **I** VOCs **I** PFCs **C** FEP High-k & gate materials **U** Doping **I** Conventional surface prep **U** Alternative surface prep **U** Non-silicon, active substrates [channel] **U** Novel memory materials **I** Lithography Mask making & clean **U** 193 immersion **U** Imprint **U** Interconnect Low-k processing **U** Copper dep processes **U** Advanced metallization **U** Planarization methods **I** Plasma etch **C** CVD chamber clean **C** Surface preparation **U** 3D via etch **C**	**Energy** Intrinsic Total fab tools (kWh/cm^2) **I** Total fab energy usage **I** Total fab support systems energy usage **I** Factory Integration Energy consumption **I** Lithography EUV **C**	**Green Fab** Intrinsic Safety screening methodologies for new technologies **U** Improvement in process chemical utilization **I** Reduce PFC emissions **C** Liquid and solid waste reduction **I** Reduce hazardous liquid waste by recycle/reuse **I** Reduce solid waste by recycle/reuse **U** Define environmental footprint metrics for process, equipment, facilities, and products; reduce from baseline year **U** Integrate ESH priorities into the design process for new processes, equipment, facilities, and products **U** Facilitate end-of-life disposal/reclaim/recycle **U** Factory Integration Fab eco-design **U** Process eco-design **I** Product eco-design **I** Design for maintenance **U** Water/utilities usage **I** Chemical usage **I** Consumables usage **U** Equipment thermal management **U** Design for End-of-Life **U** Eco-friendly facility design **I** Design for end-of-life re-use **U** Total fab water consumption **I** Total site water consumption **U** Total UPW consumption **I** UPW recycled/reclaimed **I** Exhaust and abatement optimization **U** Carbon footprint **I** Ease of decommissioning and decontamination for equipment re-use/re-claim **U**

C = Critical: Any requirement in this category is an essential item for technology success/implementation as well as ESH benefits. If not addressed, it could compromise the ability to insert the technology into manufacturing, based on potential or existing policy/regulatory issues (whether internally or externally driven) in at least one of the ITRS member regions.

I = Important: Any requirement in this category is a key item for process success as well as ESH benefits. If not addressed, it could compromise the cost of ownership (CoO) of the technology in manufacturing; based on factors such as throughput, yield, and material and/or tool costs (including disposal/abatement).

U = Useful: Any requirement in this category is a key item for ESH benefits ("best practices"), but without any clear additional factors which would place it in either of the above two categories. If not addressed, it could compromise the ability to achieve the lowest ESH impact for the technology when inserted into manufacturing.

Table ESH3a ESH Intrinsic Requirements—Near-term Years

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
I. Process and Equipment Technology Requirements									
Energy Consumption									
Total fab tools (kWh/cm^2) [2, 3] **Important**	**0.50**	**0.43**			**0.35**			**0.30-0.25**	
Water Consumption (driven by sustainable growth and cost)									
Surface preparation UPW use (% of 2005 baseline) **Important**	**90**	**80**			**75**			**50**	
Tool UPW usage (% of 2005 baseline) **Important**	**90**	**80**			**75**			**50**	
Chemical Consumption and Waste Reduction (driven by environmental stewardship and cost)									
Improvement in process chemical utilization (% of 2005 baseline) **Important**	**90**	**80**			**75**			**50**	
Reduce PFC emission **Critical**	**10% absolute reduction from 1995 baseline by 2010 as agreed to by the World Semiconductor Council (WSC)**		**Maintain 10% absolute reduction from 1995 baseline**						
Liquid and solid waste reduction (% of 2007 baseline) **Important**	**90**	**80**			**75**			**50**	
II. Facilities Technology Requirements									
Energy Consumption									
Total fab energy usage (kWh/cm^2) **Important**	**1**	**0.85**			**0.7**			**0.6-0.5**	
Total fab support systems energy usage (kWh/cm^2) [2] **Important**	**0.5**	**0.43**			**0.35**			**0.30-0.25**	
Chemical Consumption and Waste Reduction									
Reduce hazardous liquid waste by recycle/reuse** (% of 2007 baseline) **Important**	**90**	**80**			**75**			**50**	

Table ESH3b ESH Intrinsic Requirements—Long-term Years

Year of Production	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*
I. Process and Equipment Technology Requirements							
Energy Consumption							
Total fab tools (kWh/cm^2) [2]	**0.30-0.25**						
Water Consumption (driven by sustainable growth and cost)							
Surface preparation UPW use (liters per wafer pass)	**50**						
Tool UPW usage (% of 2005 baseline)	**50**						
Chemical Consumption and Waste Reduction (driven by environ-mental stewardship and cost)							
Improvement in process chemical utilization (% of 2005 baseline)	**50**						
Reduce PFC emission	**Maintain 10% absolute reduction from 1995 baseline**						
Reduce liquid and solid waste (% of 2007 baseline)	**50**						
II.. Facilities Technology Requirements							
Energy Consumption							
Total fab energy usage (kWh/cm2)	**0.6-0.5**						
Total fab support systems energy usage (kWh/cm^2) [2]	**0.30-0.25**						
Chemical Consumption and Waste Reduction							
Reduce hazardous liquid waste by recycle/reuse/reclaim** (% of 2007 baseline)	**50**						

Notes for Table ESH2a and b:
[1] CPIF = Chemical Properties Information Form
[2] cm^2 per wafer out
[3] without including EUV's influence
** as defined by SEMI guideline S23*
***Recycle = Re-use after treatment*
***Reuse = Use in secondary application (without treatment)*
***Reclaim = Extracting a useful component from waste*

Manufacturable solutions exist, and are being optimized	⬜
Manufacturable solutions are known	🟨
Interim solutions are known	◆
Manufacturable solutions are NOT known	🟥

Table ESH4a Chemicals and Materials Management Technology Requirements—Near-term Years

The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Interconnect									
Low-κ materials—spin-on and CVD **Important**	Establish PCU* and PE* baselines		Improve PCU and PE by 10% (relative) from baselines			Improve PCU and PE by 10% (relative) from previous values			
Copper deposition processes (conventional and alternative) **Important**	85% copper reclaimed/recycled		90% copper reclaimed/recycled			95% copper reclaimed/recycled			
Planarization methods **Important**	Establish consumables and emissions baselines		> 15% improvement in consumables***			2% reduction in consumables*** per year			
Plasma etch **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
CVD chamber clean (plasma) **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts.			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk		Reduce Global Warming Impact (lower GWP emissions; improved PCU*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			
Surface preparation **Important**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
Through-silicon via etch using PFCs (e.g., 3D) **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts.			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
	Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk		Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			
Front End Processes									
High-κ and metal gate materials **Important**	Conduct ESH risk assessment of materials; establish PCU* and PE* baselines		Improve PCU and PE by 10% (relative) from baselines			Improve PCU and PE by 10% (relative) from previous values			
Doping (implantation and diffusion) **Critical**	Low hazard dopant materials		Low hazard dopant materials						
Plasma etch **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
Non-silicon, active substrates (channel) **Critical**	Identify and conduct ESH risk assessments of novel materials, and establish PCU* and PE* baselines.				Improve PCU and PE by 10% (relative) from baselines				
Novel memory materials **Important**	Identify and conduct ESH risk assessments of novel wafer cleaning materials, and establish PCU* and PE* baselines.		Improve PCU and PE by 10% (relative) from baselines			Improve PCU and PE by 10% (relative) from previous values			
Lithography									
193 nm immersion resists **Important**	Establish PCU* baseline.		Improve PCU by 10% (relative) from baseline			Improve PCU by 10% (relative) from previous value			
PFOS/PFAS/PFOA** chemicals **Critical**	PFOS/PFAS/PFOA alternatives researched / implemented				Non-PFAS materials developed for critical uses in lithography				
Assembly & Packaging									

Table ESH4a Chemicals and Materials Management Technology Requirements—Near-term Years

The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Through-silicon via etch using PFCs (e.g., 3D) **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts.			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
	Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk		Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			
Emerging Research Materials									
Nanomaterials **Critical**	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.					
Materials for novel logic and memory **Critical**	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.					

** PCU (Process Chemical Utilization) = [(Feed - Output)/Feed] × 100%; PE (Process Emissions) = total of waste and byproducts emitted*
*** PFOS = perfluorooctane sulfonate; PFAS = perfluoroalkyl sulfonate, PFOA = perfluorooctanoate species*
**** Consumables = CMP pads, post-CMP brushes, filters, chamber liners, etc. (i.e., items that create solid waste)*

Manufacturable solutions exist, and are being optimized	⬜
Manufacturable solutions are known	🟨
Interim solutions are known	◆
Manufacturable solutions are NOT known	🟥

Table ESH4b Chemicals and Materials Management Technology Requirements—Long-term Years

** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Interconnect							
Low-κ materials—spin-on and CVD	🟥 Maintain or improve chemicals utilization* by 10% and minimize process byproducts						
Copper deposition processes (conventional and alternative)	🟥 100% copper reclaimed/recycled						
Planarization methods	🟥 2% reduction in consumables*** per year						
Plasma etch	🟥 Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
CVD chamber clean (plasma)	🟥 Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
	🟥 Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
Surface preparation	🟥 Alternatives with improved ESH impacts; 2% reduction in chemicals per year; recycle/reclaim						
Through-silicon via etch using PFCs (e.g., 3D)	🟥 Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%.						
Front end Processes							
High-κ and metal gate materials	🟥 Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Doping (implantation and diffusion)	🟨 Low hazard materials						
Plasma etch	🟥 Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process emissions and byproducts						
Non-silicon, active substrates (channel)	🟥 Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Novel memory materials	🟥 Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Lithography							
193 nm immersion resists	🟥 Maintain or improve chemical utilization* by 10% and minimize process byproducts; low-hazard/non-hazardous solvents, PFAS-free resists.						
PFOS/PFAS/PFOA** chemicals	🟥 PFAS-free materials developed for critical uses in lithography						
Assembly & Packaging							
Through-silicon via etch using PFCs (e.g., 3D)	🟥 Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%.						
Emerging Research Materials							
Nanomaterials	🟥 Conduct ESH risk assessment of materials.						
Materials for novel logic and memory	🟥 Conduct ESH risk assessment of materials.						

** PCU (Process Chemical Utilization) = [(Feed - Output)/Feed] × 100%; PE (Process Emissions) = total of waste and byproducts emitted*

*** PFOS = perfluorooctane sulfonate; PFAS = perfluoroalkyl sulfonate, PFOA = perfluorooctanoate species*

**** Consumables = CMP pads, post-CMP brushes, filters, chamber liners, etc. (i.e., items that create solid waste)*

[1] cm^2 per wafer out

Manufacturable solutions exist, and are being optimized	⬜
Manufacturable solutions are known	🟨
Interim solutions are known	◆
Manufacturable solutions are NOT known	🟥

Table ESH5a Process and Equipment Management Technology Requirements—Near-term Years

** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Interconnect									
Planarization methods **Important**	Establish baseline for consumables		>15% Reduction in consumables from baseline			Additional 2% reduction in consumables per year			
	Establish baseline for water usage		>15% Reduction in water usage from baseline			Additional 2% reduction in water usage per year for planarization (e.g., reduction, re-use, recycle)			
Plasma etch processes **Critical**	Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk		Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			
CVD chamber clean (plasma) **Critical**	Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk		Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved CU*) without increasing ESH risk			
Through-silicon via etch using PFCs (e.g., 3D) **Critical**	Establish PCU* and PE* baselines		Reduce Global Warming impact (lower GWP emissions; improved CU* by 10%) without increasing ESH risk.			Reduce Global Warming impact (lower GWP emissions; improved CU* by 10%) without increasing ESH risk.			
Front End Processes									
Doping (implantation and diffusion) **Important**	Low hazard dopant materials and processes		Low hazard dopant materials and processes						
	Establish energy usage baseline		Energy efficient doping processes (process and ancillary equipment)						
Plasma etch processing **Critical**	Establish PCU* and PE* baselines, and investigate alternatives with improved ESH impacts.		Improve PCU and PE by 10% (relative) from baselines, including potential use of alternatives with improved ESH impacts			Improve PCU and PE by 10% (relative) from previous values, including potential use of alternatives with improved ESH impacts.			
Novel memory materials **Important**	Identify and conduct ESH risk assessments of novel wafer cleaning materials, and establish PCU* and PE* baselines.		Improve PCU and PE by 10% (relative) from baselines			Improve PCU and PE by 10% (relative) from previous values			
Lithography									
EUV **Critical**	Conduct ESH risk assessment of processes and equipment		Minimal ESH impact from ionizing radiation and ergonomics; develop high efficiency EUV source				Minimal ESH impact from ionizing radiation and ergonomics; implement high efficiency EUV source		
Assembly and Packaging									
Through-silicon via etch using PFCs (e.g., 3D) **Critical**	Establish PCU* and PE* baselines.		Improve PCU and PE by 10% (relative) from baselines			Improve PCU and PE by 10% (relative) from previous values			
Emerging Research Materials									
Nanomaterials **Critical**	Conduct ESH risk assessment of materials, processes and equipment			Conduct ESH risk assessment of materials, processes and equipment					
Materials for novel logic and memory **Critical**	Conduct ESH risk assessment of materials, processes and equipment			Conduct ESH risk assessment of materials, processes and equipment					
New Equipment Design									
Energy Consumption (kWh per cm2) [1] **Important**	Characterize energy requirements for process and ancillary equipment.			Optimize energy consumption. Add idle capability to ancillary equipment (pumps, etc.); Set target and begin to implement energy reductions for each new technology generation					
Water and other utilities (liters or m3 / cm2) [1] **Important**	Characterize water and utilities requirements for process. Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements 15% per technology node			Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements by an established target for each new technology generation					
Chemicals (gms/cm2) [1] **Important**	Conduct ESH risk assessment of processes and equipment.			Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts; improve PCU by 10% for each new technology generation					

Table ESH5b Process and Equipment Management Technology Requirements—Long-term Years

Table ESH5b Process and Equipment Management Technology Requirements—Long-term Years

** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

Year of Production	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*
Interconnect							
Planarization methods	Additional 2% reduction in consumables per year						
	Additional 2% reduction in water for planarization (e.g., reduction, re-use, recycle)						
Plasma etch processes	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
CVD chamber clean (plasma)	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
Through-silicon via etch using PFCs (e.g., 3D)	Reduce Global Warming impact (lower GWP emissions; improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%						
Front End Processes							
Doping (implantation and diffusion)	Low hazard dopant materials and processes						
	Energy efficient deposition processes (process and ancillary equipment); reduce energy requirements by additional 25%						
Plasma etch processing	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts.						
Novel memory materials	Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Lithography							
EUV	Minimal ESH impact from ionizing radiation, ergonomics, energy consumption and source gas; maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Assembly and Packaging							
Through-silicon via etch using PFCs (e.g., 3D)	Alternative processes and equipment with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts						
Emerging Research Materials							
Nanomaterials	Conduct ESH risk assessment of materials, processes and equipment						
Materials for novel logic and memory	Conduct ESH risk assessment of materials, processes and equipment						
New Equipment Design							
Energy Consumption [1]	Characterize energy requirements for process and ancillary equipment. Optimize energy consumption. Add idle capability to ancillary equipment (pumps, etc.); reduce energy requirements by 15% per technology node						
Water and other utilities [1]	Characterize water and utilities requirements for process. Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements 15% per technology node						
Chemicals [1]	Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts; reduce chemical consumption 15% per technology node						

** Utilization = [(Feed - Output)/Feed] x 100%*
*** Consumables = CMP pads, post-CMP brushes, filters, chamber liners, etc. (i.e., items that create solid waste)*
[1] cm^2 per wafer out

Table ESH6a Facilities Technology Requirements—Near-term Years

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Facilities Design									
Eco-friendly facility design **Important**	Design facilities to minimize environmental footprint and impact			🟨 Meet a recognized standard for designing and rating a reduced environmental impact facility; e.g., LEED, Green Globes, etc.					
Water									
Total fab* water consumption (liters/cm^2) [1] **Important**	6.5	🟨 5.4			🟨 4.4			🟨 3.6	
Total UPW consumption (liters/cm^2) [1] **Important**	8	🟨 7			🟨 6			🟨 5	
UPW recycled/reclaimed** (% of use) **Important**	70	🟨 75			🟨 80			🟨 85	
Energy (electricity, natural gas, etc.)									
Total fab* energy consumption (% of 2007 baseline) [1] **Important**	100	🟨 85			🟥 70			🟥 60	
Waste									
Hazardous waste (g per cm^2) [1] **Important**	6	🟨 5			🟨 4			🟨 3.5	
Air Emissions									
Volatile Organic Compounds (VOCs) (g per cm^2) [1] **Important**	0.1	🟨 0.08			🟨 0.075			🟨 0.07	
Perfluorocompounds (PFCs) **Critical**	10% absolute reduction from 1995 baseline by 2010 as agreed to by the World Semiconductor Council (WSC)	Maintain 10% absolute reduction from 1995 baseline						🟥 Maintain 10% absolute reduction from 1995 baseline	

Manufacturable solutions exist, and are being optimized	⬜
Manufacturable solutions are known	🟨
Interim solutions are known	◆
Manufacturable solutions are NOT known	🟥

Table ESH6b Facilities Technology Requirements—Long-term Years

Year of Production	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*
Facilities Design							
Eco-friendly facility design	Meet a recognized standard for designing and rating a reduced environmental impact facility; e.g., LEED, Green Globes, etc.						
Water							
Total fab* water consumption (liters/cm^2) [1]	3.6	3					
Total UPW consumption (liters/cm^2) [1]	5	4.5					
UPW recycled/reclaimed** (% of use)	85	90					
Energy (electricity, natural gas, etc.)							
Total fab* energy consumption (kWh per cm^2) [1]	60	50					
Waste							
Hazardous waste (g per cm^2) [1]	3.5	3					
Air Emissions							
Volatile Organic Compounds (VOCs) (g per cm^2) [1]	0.07	0.065					
Perfluorocompounds (PFCs)	Maintain 10% absolute reduction from 1995 baseline						

Notes for Table ESH5a and b:
**Fab = manufacturing space + support systems*
***Recycle = Re-use after treatment*
***Reuse = Use in secondary application (without treatment)*
***Reclaim = Extracting a useful component from waste*
[1] cm2 per wafer out

Table ESH7 Sustainability and Product Stewardship Technology Requirements

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*
Sustainability Metrics																
Facilities Eco-design **Important**	Develop eco-design criteria, establishing metrics and targets for minimized environmental footprint and impact			Design facilities, process and ancillary equipment to minimize environmental footprint, and safety and health impact												
Carbon footprint **Important**	Identify common metrics and establish baseline			Reduce carbon footprint.												
Product Eco-design **Important**	Develop key environmental performance indicators (KEPIs)* and establish baseline	Reduce KEPIs 10% from baseline			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%					
Design for ESH																
Materials **Important**	Develop key environmental performance indicators (KEPIs)* and establish baseline	Reduce KEPIs 10% from baseline			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%					
	Early assessment of ESH impacts during the very early stages of R&D (when materials are being compared and selected)															
Processes **Important**	Develop key environmental performance indicators (KEPIs)* and establish baseline	Reduce KEPIs 10% from baseline			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%			Reduce KEPIs an additional 10%					
				Alternative low-ESH-impact processes for deposition and planarization				Paradigm shift to additive processing								
	Early assessment of ESH impacts during the very early stages of R&D (when processes are being compared and selected)															
Improved integration of ESH into factory and equipment design **Important**	Incorporate ESH design guidelines, methodology, and criteria into tool and factory design, e.g., LEED**															

**KEPIs = Key Environmental Performance Indicators such as energy and water consumption, product content, human toxicity, ozone depletion, global warming potential, photochemical oxidation potential, resource depletion potential, etc.*
*** LEED = Leadership in Energy and Environmental Design (a U.S. "Green Building" rating system)*

POTENTIAL SOLUTIONS

Potential solutions are outlined in Figures ESH1, 2, and 3, referring to Chemicals and Materials, Process and Equipment, and Facilities, respectively. The tables present potential solutions for Intrinsic, Interconnect, Front End Processes, Lithography, Assembly and Packaging, Emerging Research Materials, and Factory Integration; however, specific potential solutions for each area have been incorporated in the individual discussions above. Additive processing is a potential solution spanning multiple technology thrust areas, resulting in an ESH benefit through decreased chemical and resource consumption.

First Year of IC Production	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Intrinsic																
Key Environmental Performance Indicators (KEPIs) development	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Nanomaterials risk assessment methodologies & tools	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Conventional risk assessment implementation & use	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Nanomaterials risk assessment implementation & use	■	■	🟦	🟦	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Biochip development for rapid toxicity testing	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Interconnect																
Integrate KEPIs into chemical/material selection	□	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reduced ESH impact chemicals/ materials for deposition & planarization	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨
3D through-silicon via etch chemistries with reduced PFC use/emissions	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Additive processing chemistries	■	■	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨
Front End Processes																
Integrate KEPIs into chemical/material selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Alternative surface preparation chemistries with reduced ESH impact	🟦	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low CoO & high efficiency PFC process emissions abatement	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Additive processing chemistries	■	■	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨
Lithography																
Integrate KEPIs into chemical/material selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Non-PFOS/PFAS/PFOA chemistries for all chemicals/materials	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Chemicals/materials for alternative patterning (e.g., imprint, e-beam) with reduced ESH impact	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Assembly & Packaging																
Integrate KEPIs into chemical/material selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Elimination of potentially restricted chemicals/materials	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
3D through-silicon via etch chemistries with reduced PFC use/emissions	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Emerging Research Materials																
Integrate KEPIs into chemical/material selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Establish rapid ESH asssessment methods for nanomaterials	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required	■
Development Underway	🟦
Qualification / Pre-Production	□
Continuous Improvement	▨

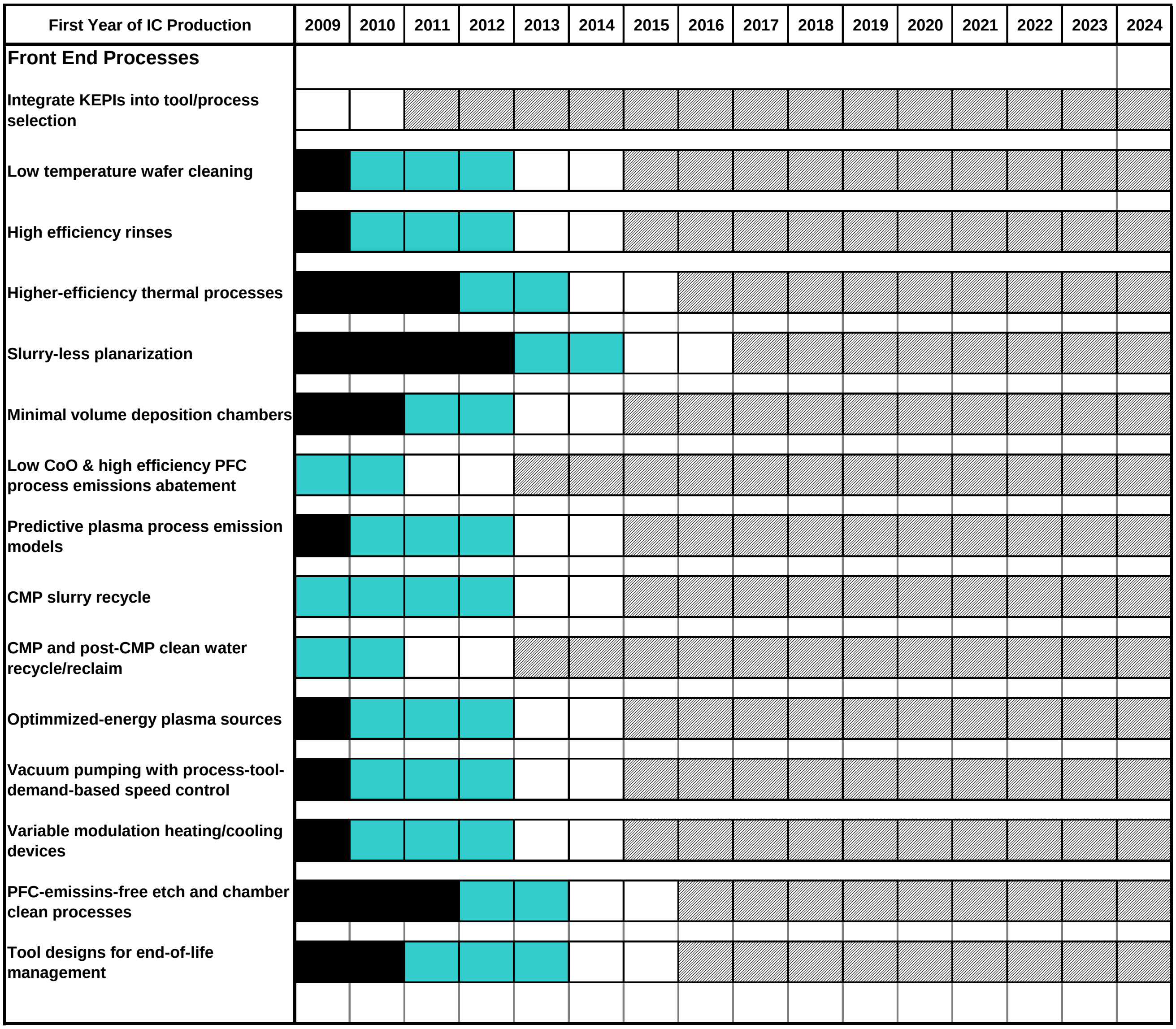
Figure ESH1 Potential Solutions for ESH: Chemicals and Materials Management

First Year of IC Production	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Interconnect																
Integrate KEPIs into tool/process selection	□	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Slurry-less planarization	■	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Minimal volume deposition chambers	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Improved throughput for ALD processes	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low CoO & high efficiency PFC process emissions abatement	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Predictive plasma process emission models	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
CMP slurry recycle	🟦	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
CMP and post-CMP clean water recycle/reclaim	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Optimmized-energy plasma sources	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low temperature wafer cleaning	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3D through silicon vias by laser drilling	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
PFC-emissins-free etch and chamber clean processes	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Vacuum pumping with process-tool-demand-based speed control	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Variable modulation heating/cooling devices	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Additive processing tools/processes	■	■	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨
Tool designs for end-of-life management	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required	■
Development Underway	🟦
Qualification / Pre-Production	□
Continuous Improvement	▨

Figure ESH2 Potential Solutions for ESH: Processes and Equipment Management



First Year of IC Production	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Front End Processes																
Integrate KEPIs into tool/process selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low temperature wafer cleaning	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
High efficiency rinses	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Higher-efficiency thermal processes	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Slurry-less planarization	■	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Minimal volume deposition chambers	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low CoO & high efficiency PFC process emissions abatement	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Predictive plasma process emission models	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
CMP slurry recycle	🟦	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
CMP and post-CMP clean water recycle/reclaim	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Optimmized-energy plasma sources	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Vacuum pumping with process-tool-demand-based speed control	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Variable modulation heating/cooling devices	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
PFC-emissins-free etch and chamber clean processes	■	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Tool designs for end-of-life management	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required ■
Development Underway 🟦
Qualification / Pre-Production □
Continuous Improvement ▨

Figure ESH2 Potential Solutions for ESH: Processes and Equipment Management (continued)

First Year of IC Production	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Lithography																
Integrate KEPIs into tool/process selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Optimized-energy EUV source	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reuse/recycle/reclaim litho cell waste streams (e.g., photoresist & ancillaries, 193i water)	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Optimized energy design for tool environmental control	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Tool designs for end-of-life management	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Assembly & Packaging																
Integrate KEPIs into tool/process selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Low/No-cure plastics	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3D through silicon vias by laser drilling	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Recyclable packaging materials	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Tool designs for end-of-life management	■	■	🟦	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨
Emerging Research Materials																
Integrate KEPIs into tool/process selection	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required	■
Development Underway	🟦
Qualification / Pre-Production	□
Continuous Improvement	▨

Figure ESH2 Potential Solutions for ESH: Processes and Equipment Management (continued)

First Year of IC Production	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Intrinsic																
Reuse/recycle/reclaim programs for consumables and spares	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Interconnect																
Improved efficiency technology for waste stream fluoride removal	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Improved efficiency technology for waste stream copper removal	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
High-efficiency centralized PFC abatement technology	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reuse/recycle/reclaim of liquid wastes	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Front End Processes																
High-efficiency centralized PFC abatement technology	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reuse/recycle/reclaim of liquid wastes	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Lithography																
TMAH reuse/reclaim	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reuse/recycle/reclaim of liquid wastes	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Factory Integration																
Develop & implement facility KEPIs	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Novel water reuse/recycle/reclaim methods	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
On-line, real-time, speciating sensors for UPW recycle	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Facility equipment optimization for energy consumption	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Idle mode integration in facility systems	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Develop & implement industry-specific LEED or similar standard	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Factory-wide modeular control approaches	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Optimize cleanroom & facility operating temperature & humidity	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required	■
Development Underway	🟦
Qualification / Pre-Production	□
Continuous Improvement	▨

Figure ESH3 Potential Solutions for ESH: Facilities